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FOOTHILLS STRUCTURE IN NORTHERN COLORADO

VICTOR ZIEGLER
Colorado School of Mines, Golden, Colo.

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INTRODUCTION

The area under discussion comprises a part of the foothills of the "Front Range" of Colorado, west and north of Denver, and extends from Morrison about 70 miles north to Fort Collins. No attempt will be made to discuss the stratigraphy of this district nor to describe any of the geological formations in detail; only the structural features will be emphasized.

STRUCTURAL FEATURES

THE FOOTHILLS MONOCLINE

The "master structural feature" of the foothills has been well described by Fenneman[1] in his discussion of the geology of the Boulder district, and also by Eldridge in the monograph on the geology of the Denver basin.[1] The following description is taken from the latter publication:

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[1] *U.S. Geol. Survey Bulletin 265*, 1905, pp. 41–43.

> The normal appearance of the foothills is that of a mountain mass of Archean rocks, fringed at an average distance of one half or three quarters of a mile by a sharp serrated ridge of Dakota sandstone, the valley between the two being occupied by the formations of the Trias and Jura. Above the Dakota come . . . . the Benton, the Niobrara—this generally constituting a second smaller reef outside the Dakota—the Pierre, the Fox Hills, and the Laramie, the basal sandstones of the Laramie again forming either a low roll in the ground or an actual comb of rock slightly projecting above the surface of the surrounding prairie. To the east of the Laramie . . . . appears in the southern portion of the area yet another comb formed by the conglomerates at the base of the Arapahoe series. Finally this is followed by . . . . the Denver formations.

To this description it is well to add that as a general rule the Lyons formation forms a prominent, though low, hogback in the strike valley to the west of the Dakota, and that in the northern part of the foothills the Archean-Fountain contact forms a prominent strike valley, and that here the Fountain is characteristically developed into a high, precipitous hogback, usually capped on its crest and dip slopes by the Lyons sandstone. Here also the Arapahoe and Denver formations are absent, and the Laramie lies almost horizontal twenty miles or more to the east of the foothills. In the southern part of the area the dips in the Fountain, Lyons, and Lykens average from 35° to 50°. These increase gradually eastward until they become vertical or even overturned in the Laramie, dips as low as 75° west being noted. Farther eastward these flatten within a few hundred feet from vertical into practically horizontal in the upper part of the Arapahoe or the base of the Denver.

No such variation is noted in the northern part of the area under discussion. West of Loveland dips of 40° are rare and occur only locally as the result of special conditions. The steepest dips occur here in the Dakota or Morrison. It is also worth noting that in the southern part of the area, where steep and overturned dips are met with, the formations have turned practically horizontal within two miles of the Archean contact—in one extreme case (at Golden) even within 4,500 feet from the contact; while in the northern part of the area dips of 15° east are found as much as 10 miles east of the Archean sedimentary contact.

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[1] *U.S. Geol. Survey, Monographs*, XXVII, 1896.

These contrasts in dips indicate that the foothills fold differs in shape and intensity over this area. The generally low dips near Fort Collins and Loveland indicate an ideal, fairly gentle, monoclinal fold, while the steep and overturned dips to the south indicate an S-shaped fold of pronounced type. The fold proper is well described by Fenneman[1] as follows:

> The master structural feature of this region is the great upturn of the strata against the mountain range. . . . . The first Archean belt west of the foothills is a dissected plateau . . . . from 6,500 to 7,000 feet above sea-level at its eastern edge, where it ends abruptly and is flanked by the Fountain sandstone. . . . . The height . . . . above the plains is nearly 1,000 feet. . . . . Five miles east of the base of the foothills the Archean surface is at least 9,500 feet below the surface, or 4,200 feet below the level of the sea. The real face of the granite plateau is therefore about 2 miles high, and this enormous rise is accomplished in 6 miles.

The opinion is also expressed that the greater part of the monoclinal flexure is the result of subsidence during the deposition of the various sedimentary formations, a conclusion passed on the assumption that the ancient shore line was located along the line of the present Front Range.

This generalization was, however, based on a small area of the foothills in which the characteristic structure is not well developed. Further, Lee[2] has proved since that all the Cretaceous formations up to and including the Laramie formerly were continuous over the present site of the Front Range. Consequently their present attitude must be due to orogenic forces, and the statement that "the process of mountain making gave to the granite plateau west of the foothills a comparatively small relative uplift above the plains" is erroneous.

A careful study of the dips and strikes of the formation south of the Boulder area and the reconstruction of a fold based on these dips as well as the occurrence of the lower formations as "inliers"

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[1] *Op. cit.*, pp. 41, 42.

[2] *U. S. Geol. Survey*, P.P. 95-C.

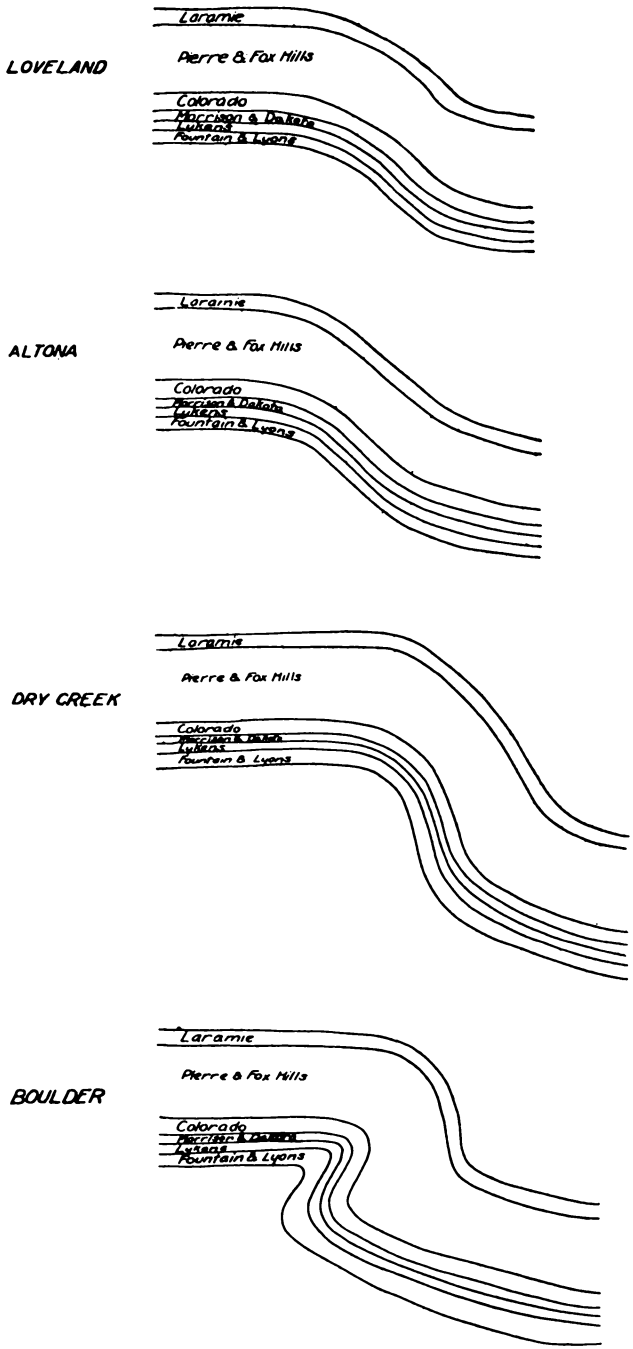

FIG. 1*a*.—Reconstructions of the original monoclinal fold of the foothills of the

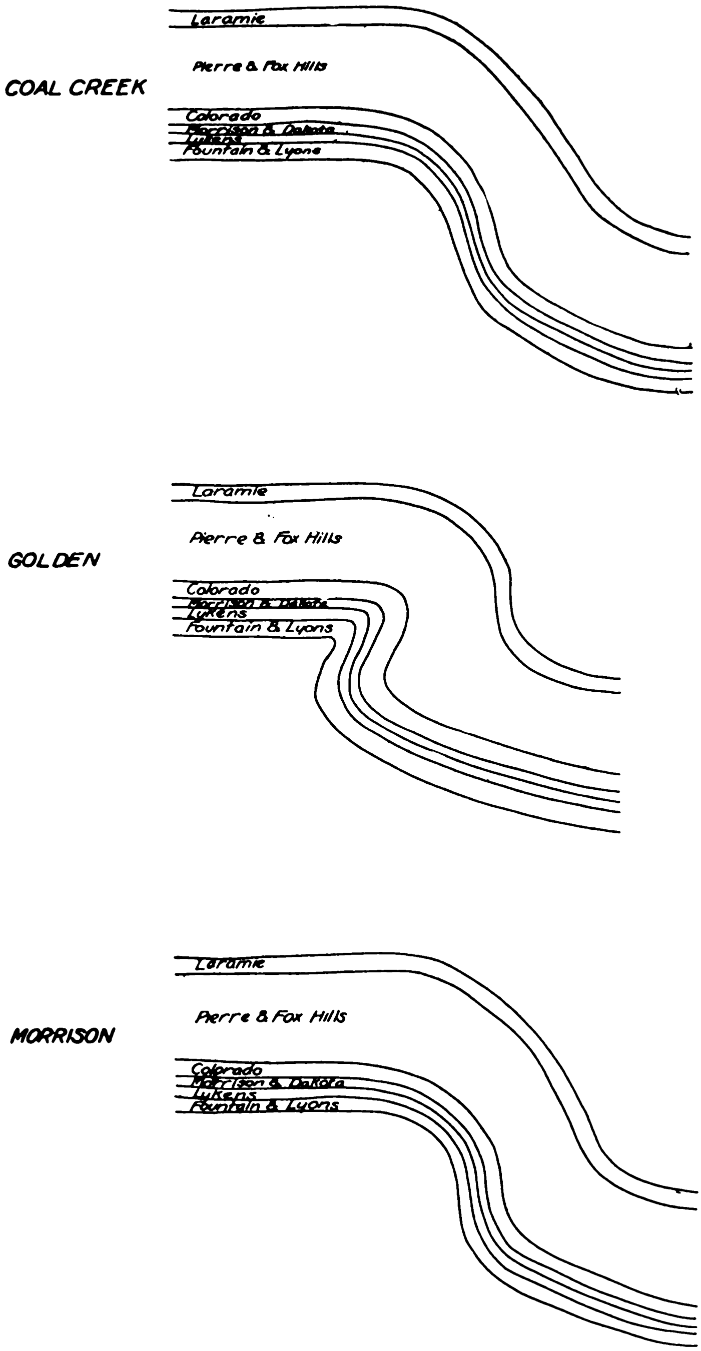

FIG. 1*b*.—Reconstructions of the original monoclinal fold of the foothills of the

in the Archean some distance west of the foothills, as for example west of Colorado Springs and also west of Loveland, furnishes good reasons for the belief that the formations underlying the Dakota also extended over the Archean, or at least for a considerable distance westward. In areas undisturbed by special local conditions, the Fountain, Lyons, Lykens, and Morrison show as close an agreement in dips and strikes with the overlying formations as would be expected for conformable rock series; and all show beautiful parallelism in folding with the younger rocks. This would be a rather peculiar coincidence, not to be expected except in rocks simultaneously folded.

The accompanying diagrams show, drawn approximately to scale, reconstructions of the original monoclinal fold worked out from dips and strikes at the localities noted. In each case faults and other local irregularities which would unnecessarily complicate the fold have not been indicated. Their possible effect, due to displacements of parts of the fold and consequent introduction of anomalous dips and strikes, has been carefully considered in each case, and, where necessary, corrections have been made in the flexure of the monocline. These reconstructions are merely intended to show the variation in the shape and curvature of the foothills monocline in its major outlines (Fig. 1, *a*, *b*, pp. 718–19).

It is interesting to note that in older interpretations of the monoclinal fold in this region the overturn is located underneath the surface and not above the surface, as the present writer has drawn it. Considering no more than the present dip and strike relationship along an east-west line at such localities as Golden or Boulder, and considering these to be located on the same horizontal plane on the monoclinal fold, no other logical interpretation is possible. If, however, the variations in dip be carefully plotted along the axis of the fold, and if we carry in mind the fact that the dips as observed at Golden and Boulder represent different horizontal planes on the monocline due to the disappearance of thousands of feet of strata, the type of overturn postulated by the writer becomes necessary in order to explain observed conditions. This will perhaps be clearer after a discussion of the structure at Golden.

LOCAL UNCONFORMITIES (SO-CALLED "ARCHES")

Certain peculiarities in the distribution of the geological formations along the foothills, especially well developed near Golden and Boulder, have been explained as the result of unconformities due to local arching in the Cretaceous sea.

The Golden area.—The sketch map of the vicinity of Golden is, with a single correction, the map by Eldridge given in his report on "The Geology of the Denver Basin."[1] The areal distribution of the formation has been well traced in this map and has proved essentially correct, while the general features of the area in question (Fig. 2) have been well described in the following words:[2]

> The topography shows a marked variation from that normal for the foothills region in general. . . . . For mile after mile along the mountains the normal topographical features may be traced with unswerving regularity, but within the area to be described they undergo rapid change, and . . . . in the vicinity of the town of Golden they are lost to recognition. For a distance of over a mile north of the town, and an equal distance south of it, the Dakota hogbacks have completely disappeared; the low Niobrara ridges cease to exist at a point about a mile north of Bear Creek, not to appear again until the region of Van Bibber Creek, 10 miles to the north, is reached; the Laramie sandstones with their coal have gradually approached to within 500 feet of the Archean at Clear Creek, the variation in their strike from that of the Triassic and Dakota outcrops below being apparent to the most casual observer. . . . . The lines of stratification are delineated clearly upon the surface and display a distinct tendency to group themselves, with respect to direction, into two well-marked assemblages—the one embracing the formations of the Colorado and all below, and maintaining for the greater part of their extent the same parallelism to the general trend of the foothills which they have held beyond the affected area; the other embracing the Montana and younger formations, and though maintaining a parallelism of strike within themselves, nevertheless abutting against the older formations, in fact approaching the range proper in a broad, well-marked, and regular inward-sweeping curve, the center of its arch lying a short distance north of Clear Creek. The features just noticed again occur, in a minor degree and in a manner not at first liable to attract attention, in the relations between the Dakota and underlying beds nearer the middle of the area, where the beds of the younger formation lie across the edges of those of the older.

[1] *Op. cit.*, p. 83.

[2] *Op. cit.*, pp. 83–84.

Eldridge discusses each geological formation in great detail, and the care with which all structural features are described is worthy of special note. Rather than cite at length from this report the writer has arranged the pertinent data given in tabular form.[1]

STRUCTURAL FEATURES AT GOLDEN

Permo-Trias (Fountain, Lyons, Lykens)

1. Rapid disappearance of strata successively from the top downward as they approach Golden. Lyons disappears 1 mile north of Clear Creek, and ½-mile south respectively. Lykens disappears about two miles north and south of Clear Creek.
2. Disappearance of Lykens is sudden north of Clear Creek; gradual to the south.
3. Discrepancy of 10° in strike with upper formations on disturbed area.
4. Normal thickness of Morrison is present where much of Lykens is missing.

Morrison

1. Missing for a distance of about 1½ miles.
2. Discrepancy in strike (10°–15°) with younger Dakota and older rocks on disturbed area—especially marked in part north of Clear Creek.
3. Sudden disappearance of Morrison north of Clear Creek; gradual disappearance south.

Dakota and Purgatoire

1. Disappears from bottom up and top down.
2. Discrepancies in strike with rocks above and below on disturbed area.
3. More sudden disappearance on north side of area.
4. Marked crumpling on north side—frequent changes in strike, not shown by Laramie, which is only 600 feet to the east.
5. Normal dip 45°. Dips 90° and overturned over disturbed area.
6. Remarkable crumpling and recumbent folding south of Golden. (Not noted by Eldridge.)

Benton and Niobrara

1. Completely disappear from top downward. Benton absent for distance of about 5 miles; Niobrara for 9 miles.
2. Conformable in dip and strike to Dakota, but not to Montana on disturbed area.
3. After disappearance of Niobrara, overlain by successively higher Montana beds as it approaches Golden.

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[1] *Op. cit.*, pp. 91–97.

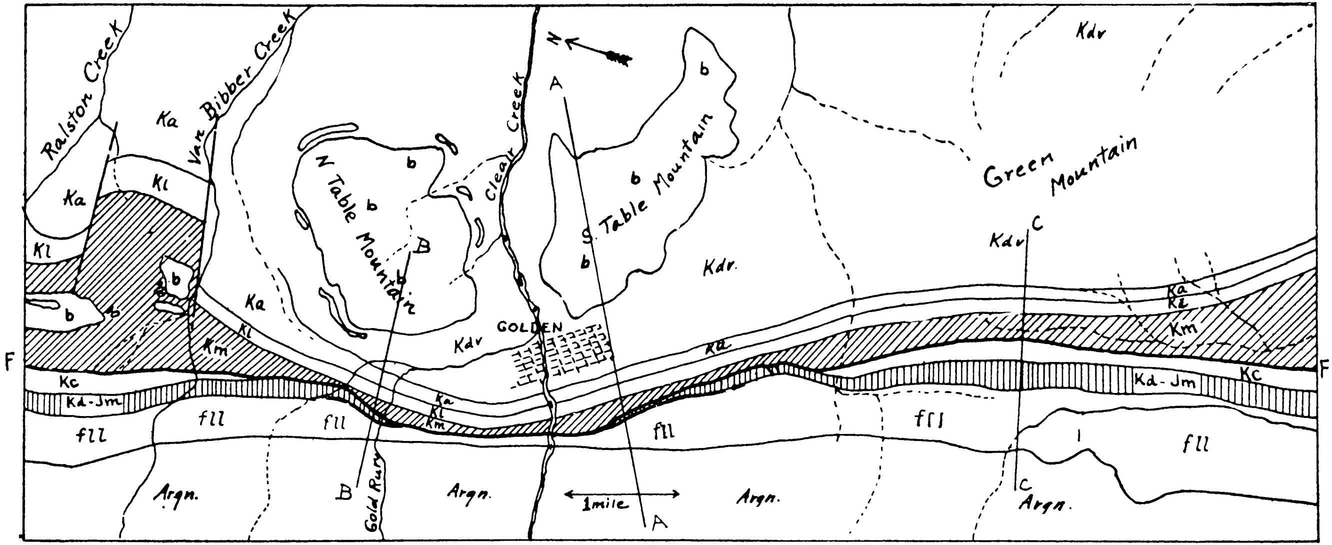

FIG. 2.—Sketch map of the vicinity of Golden. Heavy lines show faults

Argn = Archean
fll = Fountain, Lyons, and Lykens
Kd-Jm = Morrison, Dakota and Purgatoire
Kc = Colorado (Benton and Niobrara)

Km = Montana (Fox Hills and Pierre)
Kl = Laramie
Ka = Arapahoe
Kdv = Denver

Montana (Pierre, Fox Hills)
1. Pierre completely disappears from bottom upward. Absent for distance of about 4½ miles. Upper part of Fox Hills, only present at Golden.
2. Conformable in dip and strike to Laramie. Shows a discrepancy of 15°–20° in strike with older rocks.
3. Steepest dips on area at Golden—90° and overturned (80° W).

Laramie
1. Broad, sweeping curve by which it is gradually carried to the westward until at Golden it lies within 4,500 feet of the Archean.
2. No thinning.

ELDRIDGE'S HYPOTHESIS OF AN "ARCH" AT GOLDEN

The abnormal conditions tabulated above are all explained as the result of a series of unconformities at the horizons where these occur.

There is postulated a headland of anticlinal structure with axis perpendicular to the present trend of the foothills. This has been named the "Golden Arch" (Fig. 3). No attempt will be made to discuss the so-called "arch hypothesis" in detail. For such, the reader is referred to previous publications.[1] It will be noticed that the lines along which certain formations disappear are roughly parallel to the general strike of the foothills formations; and that as we approach Golden the formation to the west of such a line—that is, the older—disappears from the top down; while the formation to the east—that is, the younger—disappears from the bottom up. In the "arch hypothesis" such disappearance is explained as the result of the erosion of the older formations from the top of the rising headland, followed by a subsidence and a gradual overlapping of the younger formations against the sides and eventually over the top of this arch. The older formations are missing because of erosion; the younger, because of non-deposition.

Comments on the Arch Hypothesis: A number of points brought out in a former discussion as well as some additional data from field work seem to show serious weakness in the arch hypothesis. These points are in part facts described in detail by Eldridge and summarized above, in part facts discovered since, or at least not specifically noted by him, and in part certain fundamental

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[1] *U.S. Geol. Survey, Monographs* (1896), XXVII, 91–97.

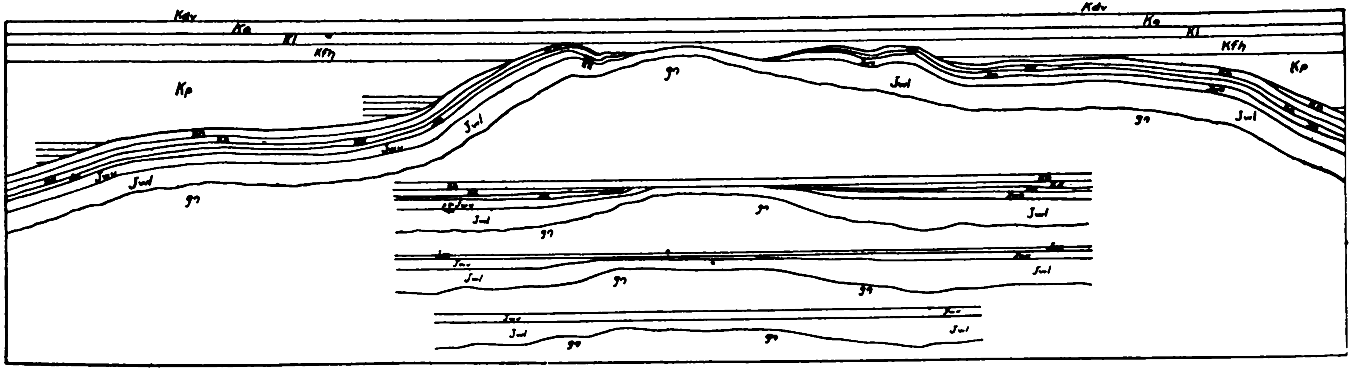

FIG. 3.—Stages in the development of the Golden arch (after Eldridge). Stages 1, 2, 3, and 4 are shown (from bottom up)

gn =Archean
Jwl =Fountain and Lyons (Lower Wyoming)
Jww =Lykens (Upper Wyoming)
Jm =Morrison
Kd =Dakota (and Purgatoire)
Kb =Benton

Kn =Niobrara
Kp =Pierre
Kfh =Fox Hills
Kl =Laramie
Ka =Arapahoe
Kdv =Denver

assumptions that appear unsound or at least unwarranted to the writer. The chief objections may be summarized as follows:

I. Objections based on facts:

1. The steepest dips occur where the formations disappear. For what reason, if their disappearance be due to an unconformity?

2. The greatest amount of overturning (60° W) is where the greatest thickness of strata is missing. The same question may be asked as for point No. 1.

3. Crumpling is common along the lines of the supposed unconformities.[1] Why?

4. Crumpling is relatively more severe on the axis of the supposed arch, that is, on the line where the greatest thickness of rock is missing. Why?

5. Crumpling is relatively more intense at those points where the formations disappear suddenly. Why this coincidence if their disappearance be due to erosion or non-deposition?

6. There is a remarkable coincidence of an association of maximum divergence of strike lines, steep and overturned dips, maximum crumpling, and the sudden disappearance of a formation. The simultaneous relationship of these to an unconformity is not clear.

7. There is an absence of shore facies in the sedimentaries. The existence of the Golden arch presupposes the existence of shore conditions, but none of the formations supposedly deposited against this arch show any change in lithological character upon crossing or approaching it.

8. No similar structures have been recognized elsewhere in the Rockies.

9. On the bluffs immediately to the south of Clear Creek the Dakota shows a dip of 60° westward, while less than 100 feet west the Fountain shows a dip of 40° eastward. These dips cannot be explained on the basis of an unconformity. (Not noted by Eldridge.)

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[1] See also H. B. Patton, "Faults in the Dakota Formation at Golden, Colorado," *Colo. School of Mines Bulletin*, III, No. 1 (1905), pp. 26–32. A complete overturn through 180° is here described.

10. There are many minor strike thrust faults clearly shown, as well as dip faults with steep fault planes and a hingelike displacement toward the east—all of which are most pronounced in the immediate vicinity of Golden.

II. Objections based on interpretation:

11. The arch hypothesis presupposes the existence of a shore line immediately to the west. The work of Lee[1] has proved the former extension of the Cretaceous formations in a continuous sheet across the entire area of the Front Range. Hence this whole area must have been an epicontinental sea, and consequently a "headland" similar to the arch could not have been present at Golden.

12. Too much oscillation required of a small local area. Such rapid alternations of up and down movements are a strain on credulity.

13. It seems incredible that an elevation sufficient to prevent the deposition of any Pierre shale could have taken place at Golden, while a few miles to the north and south the true thickness of the Pierre (7,700 feet according to Eldridge) was deposited.

14. Another weak point in the arch hypothesis is the present attitude of the strata. These if considered in the plane of their bedding form a syncline with east-west axis over the crest of the supposed arch. The limbs on each side are dipping inward as much as 35°. None of the strata show any evidence of the original anticlinal folding to which they must have been subjected in order to form the "arch." A simple calculation will show that the arch requires an anticline with average dips of at least 10° in the older rocks for 10 miles north and south of Golden, while in the crest of the arch the dips must have risen as high as 30°. Eldridge, Emmons, and Fenneman are therefore driven to the conclusion that this arch was flattened out probably in Denver time and distorted into its present shape. This requires the sudden conversion of a persistently and rapidly rising area into a remarkably rapidly subsiding one, and requires a bending in the strata similar to that of a card bent back and forth between the fingers. This whole reasoning is not only laborious but also illogical.

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[1] *Op. cit.*, p. 32.

The accumulative weight of the objections summarized above is so great that the writer unhesitatingly rejects the arch hypothesis as a possible explanation of the major structural features shown at Golden.[1] It is weak in its inherent fundamental assumptions, does not explain the many and peculiar coincidences in the facts observed along the line of the supposed unconformities, and is in several cases directly contradicted by dip and strike observations.

Proposed Explanation of the Structure at Golden: The geological conditions at Golden, outlined above, are best explained on the basis of extensive faulting practically parallel to the general strike of the formations. It is logical to believe that intense monoclinal folding of the "S" type shown to be characteristic of this part of the foothills could not be localized along a practically straight line without a decided tendency to form fractures and faults parallel to the general trend of the fold. On the accompanying geological sketch map of the vicinity of Golden the location of such faults is indicated by heavy lines, and it will be noted that these coincide with the lines of two of the unconformities of Eldridge in his arch hypothesis. The accompanying sections show in detail the faulting as postulated by the writer. In the case of section *A-A*, the double fault and its effect on the strata in the monoclinal fold is shown by a reconstruction of the latter in its original condition preceding each displacement (Figs. 4–7).

It will be noted that the faults are considered to have steep westward dips. The author has arrived at this conclusion from a study of the relationship of the course of the fault line to the topography, from a consideration of the character of the monoclinal fold, and the effect of the fault on the displaced rock formations. Ordinarily a thrust fault with dips as steep as indicated would be considered unusual, but we must carry in mind the fact that, in most cases of thrust faulting, lateral pressure is the dominant cause —as, for example, in the southern Appalachians. Here, therefore, thrust faults are as a rule characterized by flat dips. In the case of a monoclinal fold such as this, however, the maximum pressure

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[1] Richardson, *U.S. Geol. Survey*, Folio 198, p. 11. It is of interest to note that both Lee and Richardson appear to doubt the truth of the arch hypothesis. In this connection see Lee, *op. cit.*, p. 32.

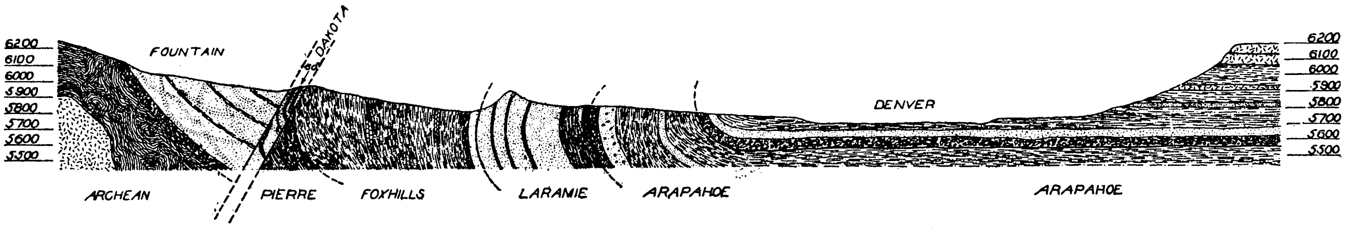


FIG. 4.—Structure section along east-west line through Golden

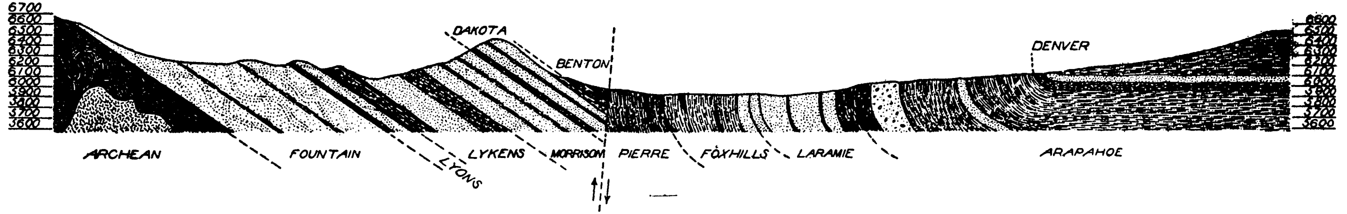
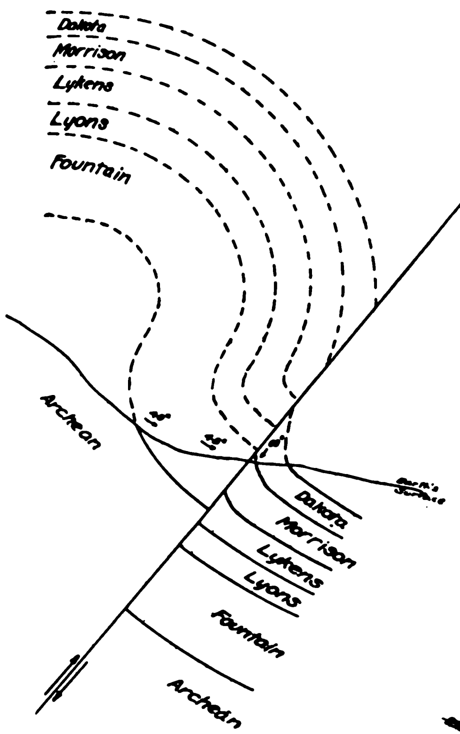


FIG. 5.—Structure section along east-west line, about four miles south of Golden

must have been nearly vertical and must have been manifest at the edges of the uplift in severely crowding the strata upon each other, owing to slipping and sliding on the steeply inclined Archean floor. Under these conditions the most logical planes of slipping would be the bedding planes, and the resulting faults would be strike faults with steep dips. The general dip and strike relationship shows normal easterly dips to be the rule in the older formations to the west of the fault plane, while the younger rocks to the east are characterized by overturned westerly dips. A consideration of the monoclinal fold will show that only a steep westward-dipping thrust fault as drawn by the writer can explain this relationship. Any eastward-dipping fault with overthrust from the east would bring younger horizontal rocks to rest upon



First Fault East of Tunnel House

FIG. 6.—Detail of first fault shown on Fig. 4.

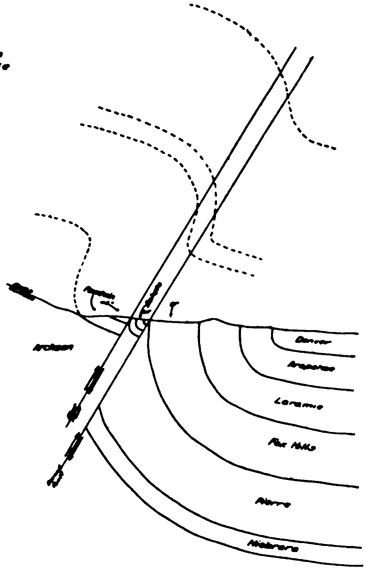


FIG. 7.—Detail of second fault (eastern one) shown on Fig. 4.

older steeply dipping ones, which is not the case. As will be seen from the sections, these faults are of the hinge type, with maximum displacements at Golden. This gradually decreases to zero toward the north and south.

All facts recorded by Eldridge and all facts observed by the writer accord perfectly with such an explanation. We should expect fault lines of this nature to be characterized by the crumpling and overturning of strata affected. The more sharply a formation is truncated the more evident the effects on its bedding planes should be. Maximum displacement and maximum disturbance should logically go hand in hand. The course of the fault plane and its position would determine whether a formation disappears from the bottom up or from the top down. As a general rule, with dips and strikes as observed, the formation on the west side of this fault plane should disappear from the top downward, while the formation on the east side should disappear from the bottom up. This is actually the case (Fig. 8).

Upon cursory examination the decided westward curve of the outcrops is somewhat surprising and seems to suggest that the eastern block represents the upthrow side. This is, however, not true, and the inward curve is the combined result of the gradual steepening and eventual overturning of the monoclinal fold as we approach Golden, and the displacement along the westward-dipping fault surface.

The actual inward sweep of the strata resulting from the writer's interpretation of the structure can readily be approximated as follows: The total thickness of strata actually cut out at Golden is about 10,000 feet. Therefore, the lowest bedding plane on the Fox Hills remaining at Golden must have been located at least 10,000 feet higher than its present position on the monocline before faulting. To this must be added the difference in elevation between the top of the Archean and the Fox Hills today (at least 1,200 feet) and a certain amount to allow for folding, hence 12,000 feet may be considered a safe estimate as to the minimum amount of throw necessary to bring the base of the Fox Hills from its original location in the monocline to its present position. A vertical drop of 12,000 feet on a fault plane dipping 55° westward will result in a westward travel of 8,000 feet on the horizontal plane. The result of the displacement alone will be a decided westward heave in any

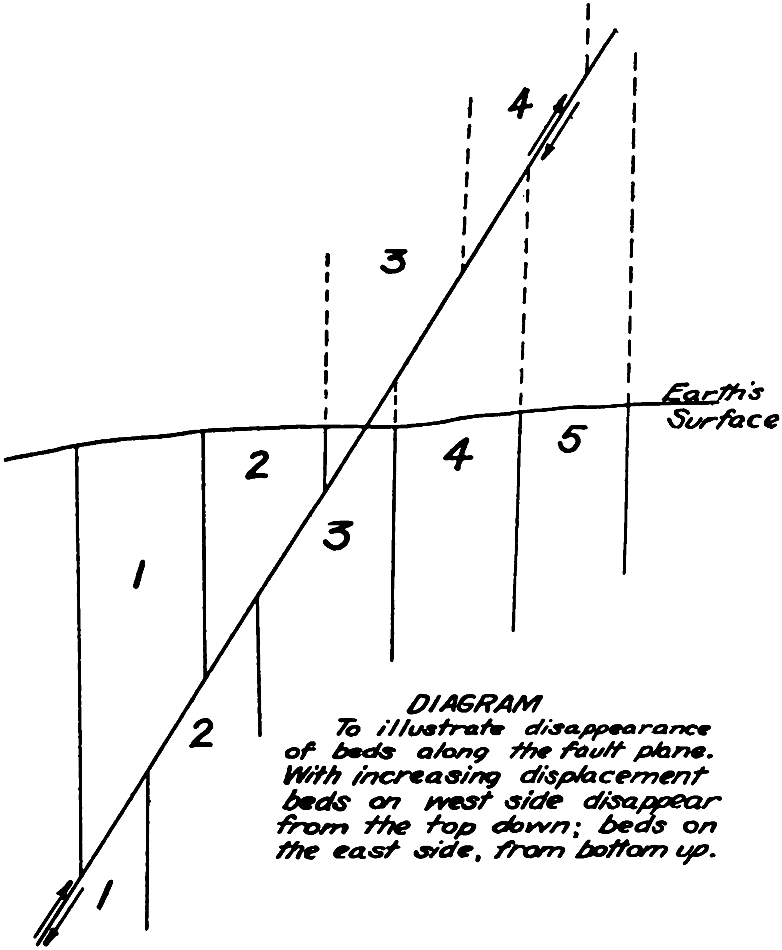

4
3
Earth's Surface
2
4
5
1
3
2
1
DIAGRAM
To illustrate disappearance of beds along the fault plane. With increasing displacement beds on west side disappear from the top down; beds on the east side, from bottom up.

FIG. 8.—Diagram illustrating the disappearance of beds along the fault plane. Older beds (on left) disappear from top down; younger beds (on right) disappear from bottom up.

outcrop, and, since the amount of westward travel is dependent upon the amount of throw, each outcrop should show a progressively larger travel toward the west as we approach Golden.

This westward travel of 8,000 feet, due to the fault, will be augmented considerably by the change in the character of the monoclinal fold. As has been shown above, the monocline north and south of Golden is normal, gradually steeping and eventually overturning as it approaches Golden. The natural dip of the formations in the normal parts would, therefore, carry their outcrops far to the east of the steeper and overturned parts of the monocline, which, added to the effect of the faulting, is undoubtedly sufficient to account for the present situation of the various formations.

In connection with the writer's interpretation the following statement from Marvine[1] referring to the condition at Golden is of interest: "Some of the facts at hand indicate that a peculiar fault, depending on the nature of the sharp fold, and possibly connected with the lava near by, may have caused the present appearance."

The true nature of the fault was not realized by Marvine, for he also states "this may be caused . . . . by a fault which has pushed the higher portion of the series westward over the upturned edges of the lower portion, thus concealing much of the latter." Such a displacement is, however, incompatible with the data at hand and was hence rejected by later workers.

It is also of interest to note that Lee and Richardson[2] appear to doubt the existence of local unconformities in the foothill region. Dr. Patton also states in personal conversation that many of the phenomena observed by him in the foothills appear to be incompatible with the arch hypothesis.

The Boulder area.—The same structural peculiarities are shown at Boulder as at Golden, but not developed to the same remarkable degree and differing in some minor detail. Eldridge,[3] and subsequently Fenneman,[4] studied this area in detail and developed an explanation in every respect similar to that advanced for the conditions at Golden (Fig. 9). Elsewhere[5] the writer

[1] *Hayden Survey*, VII (1873), 137, 138.

[2] See Lee, *op. cit.*, p. 32; Richardson, *U.S. Geol. Survey*, Folio 198, p. 11.

[3] *U.S. Geol. Survey, Monographs*, XXVII, 105–14.

[4] *U.S. Geol. Survey Bulletin 265*, pp. 54–66.

[5] *Colo. School of Mines Quarterly*, April, 1917.

has discussed the Boulder area in detail and has shown that in this district also it fails to account for the local structural features and is fundamentally as unsound here as it is at Golden.

The accompanying sections show the writer's interpretation of the structure at Boulder. Here, as at Golden, steeply dipping strike faults have taken place parallel to the general trend of the foothills monocline, which are responsible for the disappearance of some formations and the notable decreases in thickness exhibited by others. The writer will not attempt to discuss these faults in detail. They resemble in every respect the faults at Golden and affect the strata in a similar way, but to a lesser extent. They are in absolute harmony with the manner of disappearance and thinning of the various formations, with observed dip and strike relationships, and do not postulate the extreme local subsidences and elevations required of the older explanation (Fig. 10).

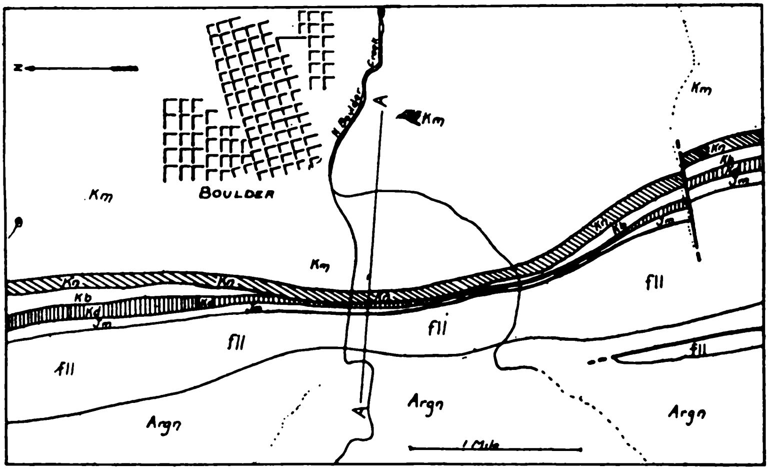


FIG. 9.—Sketch map of vicinity of Boulder (after Eldridge). Heavy lines indicate faults. For symbols, see Fig. 2.

Minor structural features.—Much minor faulting and folding, some of it of eccentric type, characterizes the great monoclinal uplift. Elsewhere[1] the writer has discussed this in some detail, especially for the purpose of bringing out the relation existing

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[1] *Op. cit.*

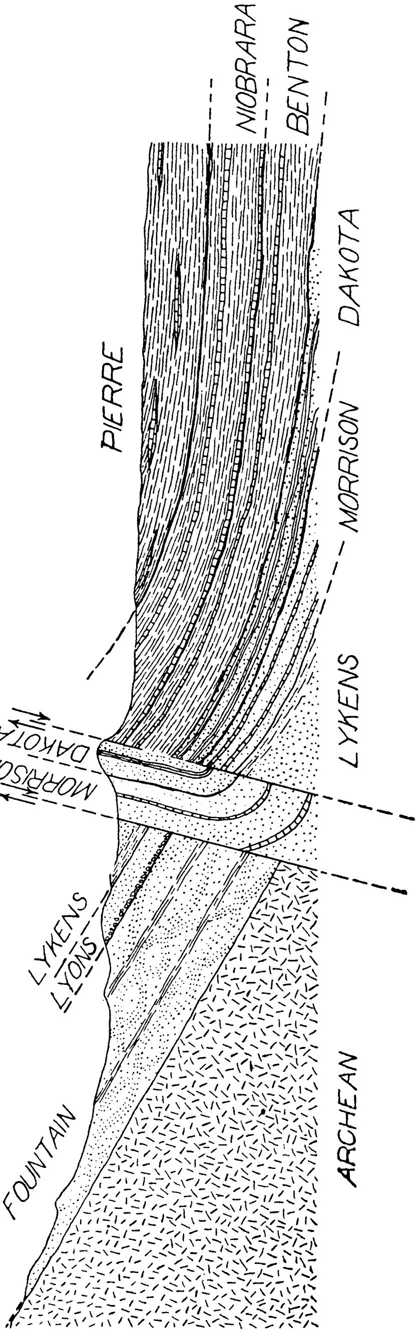

FIG. 10. East-west structure section through city of Boulder

between these minor structures and the huge thrust faults here described (Figs. 11–15).

Minor Folds: Two distinct types of minor folds can be recognized, *folds en échelon* and *drag folds*. The former pass practically invariably on their west flank into eastward-dipping faults with strikes nearly parallel to the axis of the fold. They represent minor wrinkling, with overthrusts from the east subordinate in amount to the main monoclinal uplift and faulting. Other folds, noted especially in the shale series, represent adjustments by incompetent layers to stresses incident to the formation of the uplift.

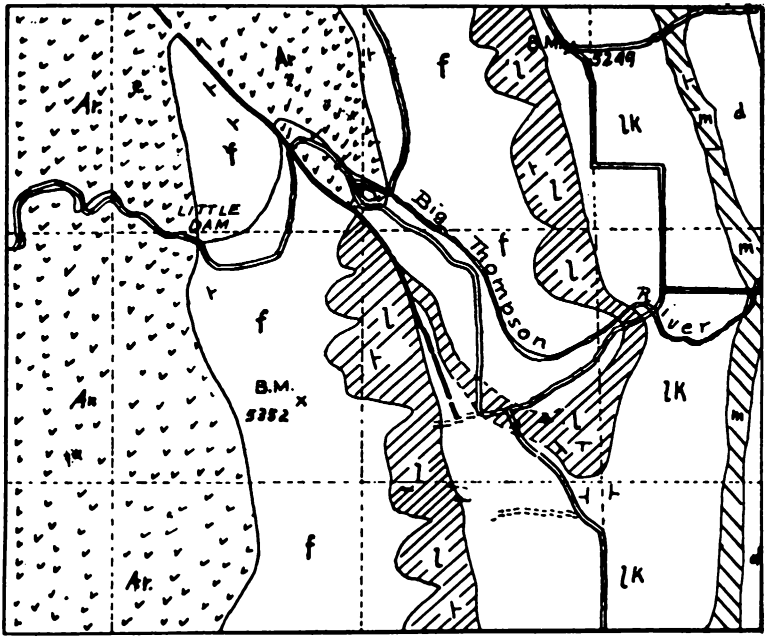

FIG. 11.—Geological sketch map of area on Estes Park road west of Loveland, showing characteristic fold *en échelon* and accompanying thrust fault. Section lines are indicated.

Minor Faults: Both strike and dip faults are numerous, especially in the structurally disturbed areas at Golden and Boulder. They are all of slight displacement. They do not antedate the uplift of the monoclinal fold, as stated by Eldridge, Fenneman, etc., but represent minor fracturing and slipping attendant upon, and consequent to, the formation of the main monoclinal uplift and its master-faults.

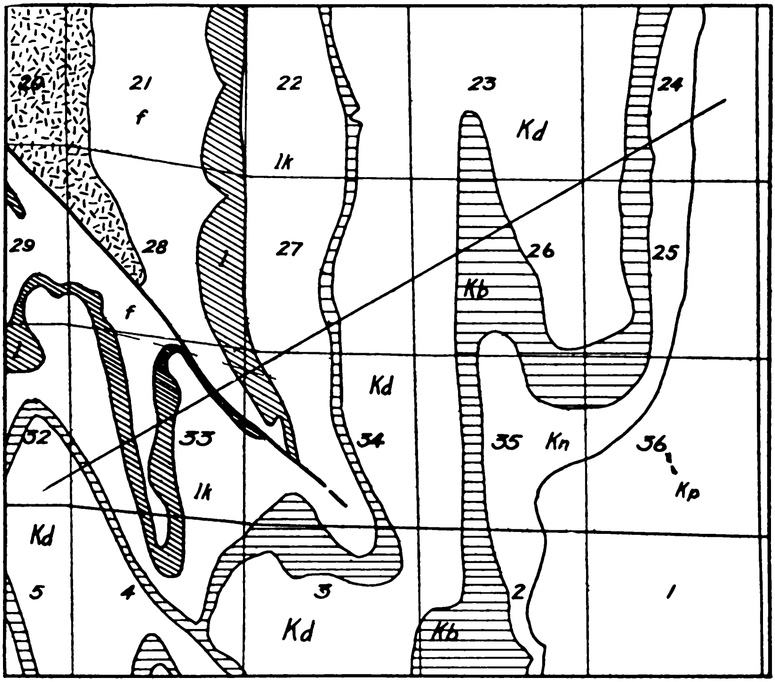

FIG. 12.—Geological sketch map of southwest corner of Loveland quadrangle, showing folds *en échelon*. For symbols, see Fig. 2.

SUMMARY

The master-monocline.—It has been shown by a reconstruction of the original foothills fold from observed dip and strike relationships that this represents an ideal monoclinal fold in strata originally continuous over the entire area of the Front Range, which gradually steepens and eventually overturns as it approaches Boulder and Golden. Contrary to former interpretations and general belief, the maximum overturn is above the earth's surface.

The main faults.—It has definitely been proved that the structural irregularities at Golden (and Boulder) cannot be explained

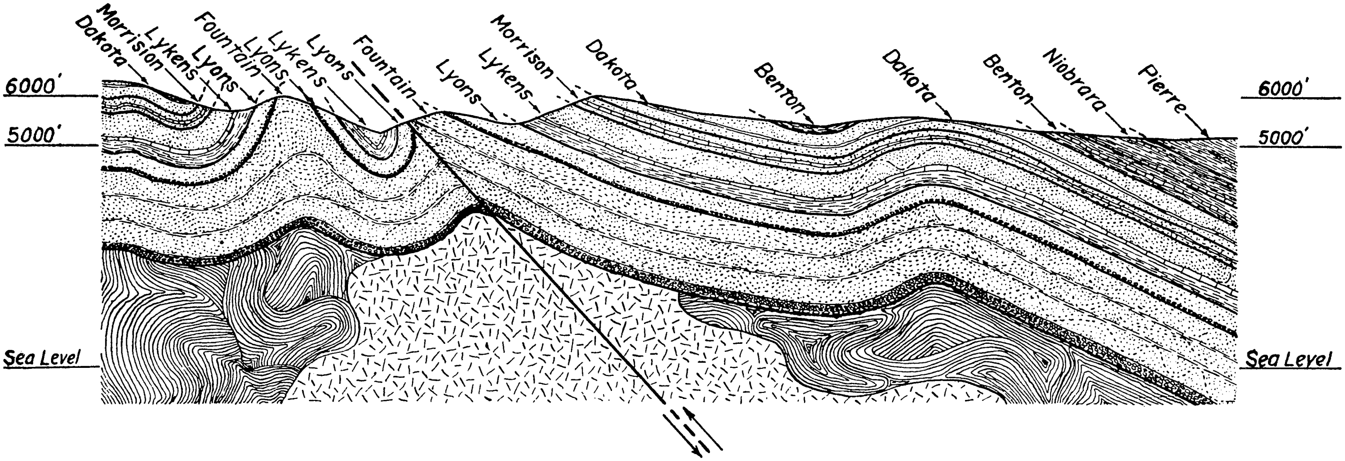

FIG. 13.—Section along line indicated on Fig. 12

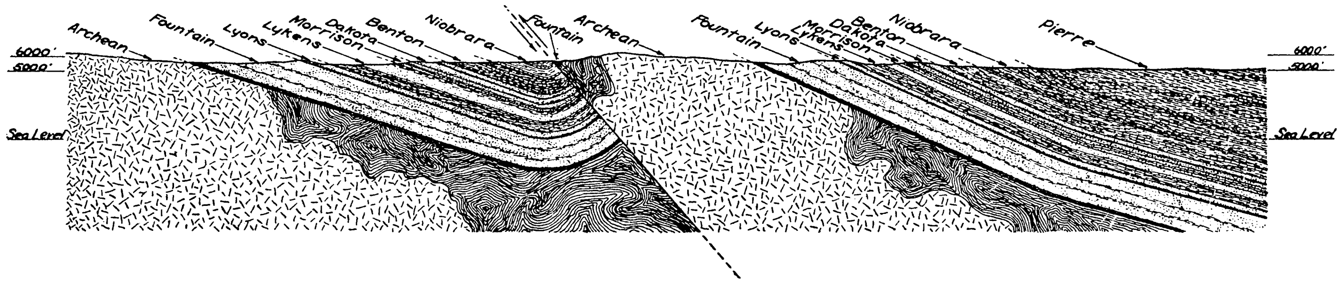

FIG. 14.—Huge fold *en échelon* and fault west of Loveland, east-west section, through Mt. Milner

as the result of repeated local arching and contemporaneous erosion, as attempted by former workers in this field. An alternative interpretation has been advanced by the writer which

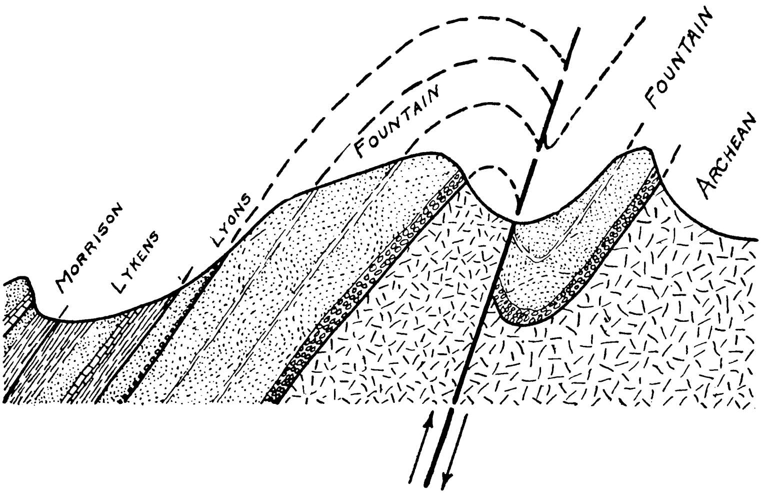

FIG. 15.—Fold *en échelon* of the Twin Peaks at Boulder. East-west section

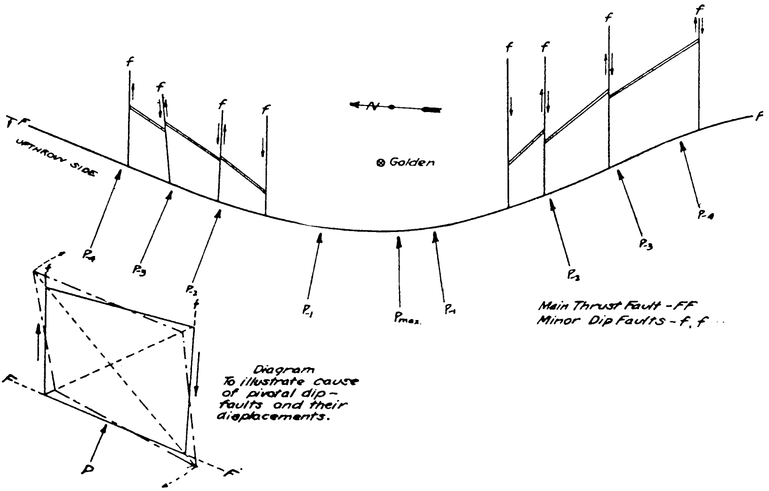

FIG. 16.—Diagram to illustrate the displacement of the dip faults and their relation to the large thrust faults at Golden. Small diagram shows distortion of interfault block due to pressure causing the main fault. The small arrows indicate the direction of displacement of interfault blocks.

postulates the presence of extensive strike faults with steep westerly dips and overthrust from the west. This interpretation is shown to be free from the inherent weaknesses of the older so-called arch hypothesis, and to be in perfect accord with all observed geological features.

Conclusion.—The formations represented in this area of the foothills range in age from Permo-Carboniferous to Paleocene. The Cretaceous formations certainly, the older probably, extended formerly over the entire area of the Front Range. At the close of Arapahoe time and during early Denver time the area to the west of the foothills rose, and the sedimentaries were folded into a normal monocline with average eastward inclination of about 45°. Locally (as at Golden and Boulder) excessive overturning occurred, accompanied by fracturing, and resulting in extensive overthrusts from the west along steeply dipping fault planes. Minor strike faulting, and dip faulting with hingelike displacements, as well as drag folding, accompanied and followed the major uplift and faults. The natural buckling and wrinkling of strata, where the pressure on the monoclinal fold was not intense enough to cause huge strike faults, resulted in the formation of folds *en échelon*, with their attendant overthrust faults from the east. The exact time of the uplift cannot be closely determined, except that the basal beds of the Denver are involved in the folding and that the composition of the upper beds of this formation shows that erosion had entirely cut through the sedimentary series over the site of the Front Range at the time of their deposition.

The sincere thanks of the writer must be expressed to Dr. H. B. Patton for advice and helpful suggestions in the preparation of this paper.